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INTEGRATED OPTIC SIGNAL PROCESSORS
FOR WIDEBAND RADAR SYSTEMS

ANNUAL TECHNICAL REPORT II

PREPARED FOR

Ballistic Missile Defense Advanced

Technology Center

Contract DAS G 60-78 C-0122

For The Period

July 15, 1978 - January 30, 1980

Prepared By

Professor Chen S. Tsai, Principal Investigator

Department of Electrical Engineering

Carnegie-Mellon University

Pittsburgh, Pa. 15213

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The general objective of this research program is to explore the potential of integrated acoustooptic technology with application to wideband radar systems. The potential of acoustooptic (AO) devices for real-time processing of wideband radar signals has been well recognized. Accordingly, implementation of AO signal processors using integrated optic techniques constitutes one of the most important on-going R and D activities. The major objectives of this research are to

(Continued on Next Page)

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carry out research on integrated acoustooptic signal processing including pulse compression, convolution, and correlation. Thus specific tasks of the research are: (1) to further explore guided-wave AO pulse compressors and convolvers, and (2) to initiate research on guided-wave AO correlators. Some very encouraging progress has been achieved with each subarea.

With regard to the pulse compressors, theoretical and experimental studies have been carried out. The theoretical study has identified the key parameters. On the experimental study, additional measurements were made to correlate with the theoretical predictions. A good agreement between the measured values and the predicted has been achieved. A 5 nsec width of the compressed optical pulse and a time-bandwidth product of 300 were obtained using a linear FM pulse of 430 MHz center frequency and 160 MHz bandwidth. With regard to the convolvers, a detailed coupled-mode analysis aiming at determining the ultimate performance figures of the acoustooptic convolvers such as bandwidth, time-bandwidth product, and dynamic range is near completion. The findings of this study will be useful for design of a convolver of larger bandwidth and larger time-bandwidth product than the preliminary convolver which has been demonstrated experimentally.

With regard to the time-integrating correlators, our preliminary experiments using surface acoustic waves (centered at 125 MHz) in a Y-cut $LiNbO_3$ waveguide and a He-Ne laser light (6328 Å), modulated by a bulk-wave AO modulator and coupled into and out of the waveguide through a pair of rutile prisms, have demonstrated a processing time of 7 milliseconds and a time-bandwidth product of 1.5×10^5. A model design using hybrid structure has shown that a Y-cut $LiNbO_3$ plate having a substrate area of 2.5x6 cm is sufficient to accommodate all passive and active components. Based on the aforementioned preliminary results, this hybrid module should be capable of providing much better performance figures. Some encouraging results have been obtained. We have successfully butt-coupled a He-Ne laser light at 6328 Å to the $LiNbO_3$ waveguide and butt-coupled the Bragg diffracted light out of the $LiNbO_3$ waveguide. We are in the process of mastering the technique for fabricating geodesic lenses. We expect no major difficulty in realizing a preliminary module once the geodesic lenses are fabricated.

In view of the great current interest in Bulk-wave acoustooptic time-integrating correlators and the many inherent advantages with the Integrated-Optic version, and the fact that considerable progress has been made under the BMDATC support, we plan to continue this research if BMDATC can provide the necessary support in the near future. The specific tasks of this projected research are: 1. to complete the implementation of the hybrid integrated optic time-integrating correlator; 2. to study its performance characteristics/figures; 3. to establish design parameters and guidelines, and ultimate capabilities; 4. to identify and study suitable signal processing architectures.

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INTEGRATED OPTIC SIGNAL PROCESSORS
FOR WIDEBAND RADAR SYSTEMS

ANNUAL TECHNICAL REPORT II

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INTEGRATED OPTIC SIGNAL PROCESSORS
FOR WIDEBAND RADAR SYSTEMS
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ANNUAL TECHNICAL REPORT II

I.   INTRODUCTION

A.   Integrated Optics Technology

Integrated Optics is an emerging technology that has been actively pursued in recent years.[1] The ultimate objective of integrated optics is to realize miniature optical components such as light sources, modulators, switches, deflectors, lenses, prisms, and detectors in a substrate to perform various useful functions. Like the existing integrated electronics in which a large number of active and passive components such as transistors, diodes, resistors and capacitors are packed in a small area semiconductor chip, the integrated optics, when fully developed, are expected to have many advantages over the existing bulk optical systems. Some of the advantages of the miniature components over their bulk counterparts are smaller size and lighter weight, wider bandwidth, lesser electrical drive power requirement, greater signal accessibility and integratability. The miniature components are also expected to possess advantages in stability, reliability, ruggedness and ultimate cost.[1]

It has now been well recognized that the most immediate and important applications of integrated optics lie in the areas of wideband multichannel communications (for both military and civilian) and signal processings (for military hardwares such as radars).[2] With regard to communications, a number of first-generation low data rate laboratory and field test systems have been built and their performance have demonstrated their potential. With regard to signal processings, the research and development efforts have just begun.[3,4]
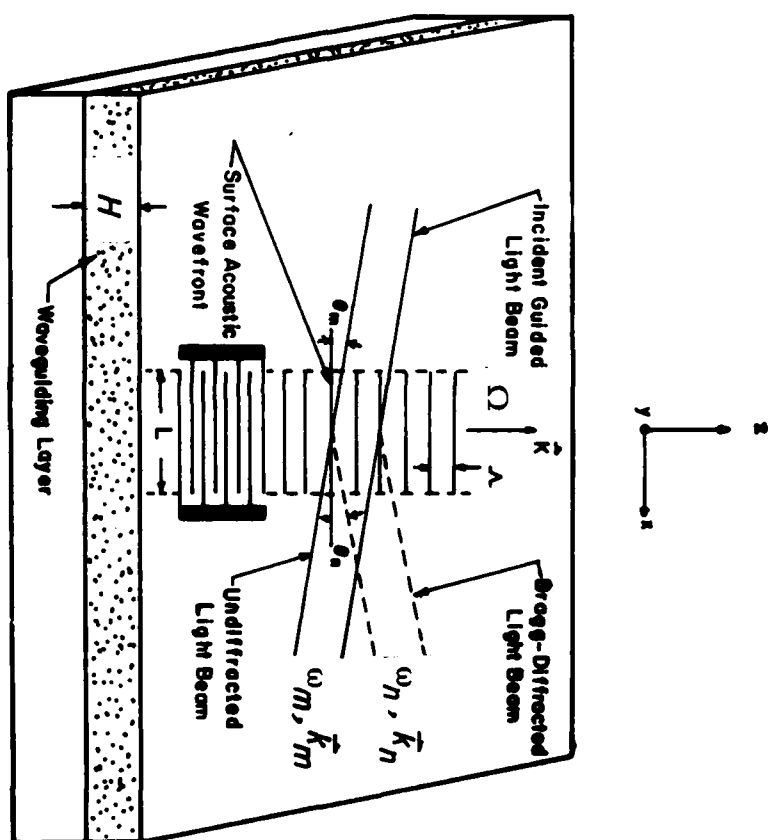
Fig.1 Guided-Wave Acoustooptic Bragg Diffraction
From A Single Surface Acoustic Wave

B.　Guided-Wave (Thin-Film) Acoustooptics

An acoustic (sound) wave can induce a significant change in the refractive index of a material and thus create an optical grating to diffract a light beam. This sound-light interaction, commonly called the acoustooptic interaction, was discovered as far back as 1932 and was studied in many liquids up to early 1950's. These earlier studies employed incoherent light sources and bulk acoustic waves of relatively low frequency. Since 1965 a great deal of R and D work on this subject have been carried out in a variety of solid materials using coherent light sources and bulk acoustic waves of much higher frequency. This surge of activity was mainly due to the advant of the lasers and the advancement in the bulk acoustic wave transducer technology. Various types of bulk-wave acoustooptic devices such as the modulators, scanners, switches and filters for a laser beam as well as the data processors for radio frequency signals have now become available commercially and are being deployed in a variety of applications.

Recent research on acoustooptic interaction involves a new form of interaction configuration in which both the coherent light wave and the acoustic wave are guided in a planar substrate (Fig. 1). A wave is said to be guided if its energy is confined in a thin layer beneath the substrate. The extension of research on acoustooptic interaction to the guided-wave (thin-film) form described above was motivated by the recent emergence in surface acoustic waves technology[5] and the integrated optics technology described earlier. A surface acoustic wave (SAW) can be generated by applying a radio frequency signal across an interdigital finger electrode pattern deposited on a piezoelectric substrate. Surface acoustic waves propagate on a material substrate and has most of its energy contained in a thin layer right beneath the surface. As indicated earlier, the integrated optic systems when fully developed are expected to have a number of advantages over the existing bulk optical systems. Specifically, the thin-film acoustooptic devices, in comparison to their bulk-wave counterparts, possess inherent advantages of requiring less electric drive power, being smaller, lighter in weight, less susceptible to environmental effects, and more integratable, and thus potentially less costly.

C-MU has been actively engaged in research on new guided-wave acoustooptic and electrooptic devices with applications to future wideband multichannel integrated/fiber optic communication and signal processing systems. Through the supports of various government agencies a number of novel concepts and devices have been discovered and developed. For example, several techniques for wideband

guided-wave light beam deflection and switching have been developed under the supports of the NSF and the ONR.[6] For example, a composite bandwidth as large as 500 MHz has been demonstrated in a device which was fabricated in a Y-cut LiNbO$_3$ waveguide.[7] To provide an appreciation of this bandwidth we note that a 500 MHz bandwidth acoustooptic light beam scanner is capable of deflecting a light beam of 1 cm aperture into 1,400 resolvable beam diameters, requiring a switching time of 2.4 x 10^{-6} sec between any two resolvable beam diameters.
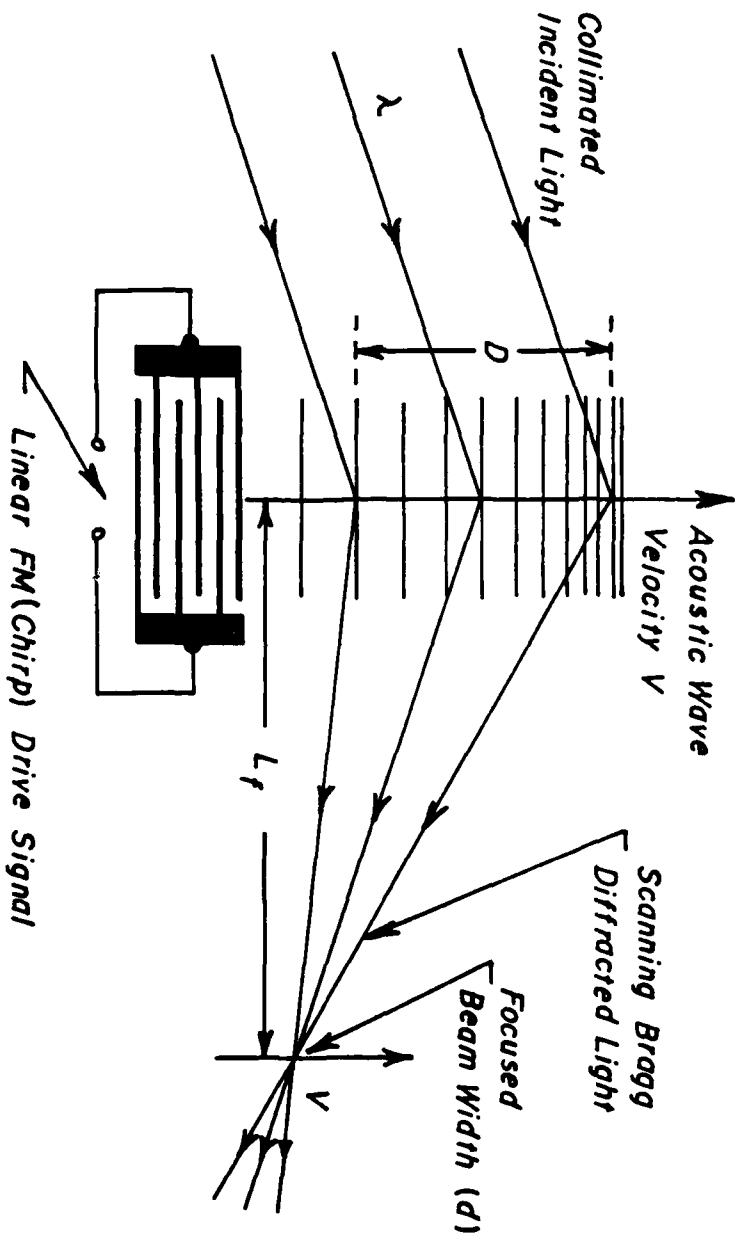
Development of these wideband techniques has made possible to design and fabricate high-performance thin-film acoustooptic (AO) devices, and has thus paved the way for the realization of a variety of potential applications.[7] These potential applications include high-resolution light beam deflectors, spectrum analyzers, convolvers, pulse compressors, correlators, multiplexers/demultiplexers, and tunable optical filters. For example, a number of military and civilian laboratories are currently using wideband thin-film acoustooptic deflectors to develop an integrated acoustooptic spectrum analyzer for data processing of very wideband ratio frequency signals.[4-8] A spectrum analyzer is used to measure the frequency components as well as their relative strength contained in a complex radio frequency signal.

II. RESEARCH OBJECTIVES

The general objective of this research program is to explore the potential of integrated acoustooptic technology with application to wideband radar systems. The potential of acoustooptic (AO) devices for real-time processing of wideband radar signals has been well recognized.[9-11] Accordingly, implementation of AO signal processors using integrated optic techniques constitutes one of the most important on-going R and D activities.[12-14] The major objectives of this research are to carry out research on integrated acoustooptic signal processing including pulse compression, convolution, and correlation. Thus specific tasks of the research are:

(1) to further explore guided-wave AO pulse compressors and convolvers, and

(2) to initiate research on guided-wave AO correlators.

Some very encouraging progress has been achieved with each subarea.

Collimated Incident Light

λ

D

Acoustic Wave Velocity V

Linear FM (Chirp) Drive Signal

Scanning Bragg Diffracted Light

Focused Beam Width (d)

L_f

V

Focal Length $L_f = \dfrac{DV}{\lambda \Delta f} = (\dfrac{V^2}{\lambda})(\dfrac{\tau}{\Delta f})$

Focused Beam Width $d \approx \dfrac{V}{\Delta f}$

Scanning Velocity $= V$

Where $\begin{cases} \Delta f = \text{Bandwidth Of Linear FM Drive Within Beam Aperature D} \\ \tau = \text{Acoustic Transit Time Across Aperature} = \dfrac{D}{V} \end{cases}$

FIG. 2   Guided−Wave Acoustooptic Light Beam Deflection Using Analog Mode Of Operation

III. GUIDED-WAVE ACOUSTOOPTIC PULSE COMPRESSORS

A. Technical Discussion

One of the commonly used RF pulses which can provide long range and good range resolution in radar is the so called linear FM pulse (chirp pulse) in which the carrier frequency varies linearly within the pulse. By means of a signal processing technique referred to as "radar pulse compression" at the receiver, the feeble radar echoes may be made sharp and strong. Thus, the characteristics of a radar pulse compressor are the width and the intensity of the output compressed pulse. The pulse width Δt is approximately equal to $1/B$, where B is the bandwidth of the chirp pulse. The pulse intensity is enhanced over that before pulse compression by a factor equal to TB, commonly called the compression ratio or time-bandwidth product, where T is the width of the chirp pulse.

The potential of real-time processing of radar chirp RF signals using coherent acoustooptic approaches have long been recognized.[9] As a matter of fact, AO pulse compressors of various configurations using bulk-wave AO cells have been examined in recent years.[9,10] These AO pulse compressors have been shown to be capable of processing a wide variety of signal codes and waveforms. The capacity of such bulk ve AO pulse compressors is mainly limited by the bandwidth of the AO cells. In a guided-wave AO pulse compressor (See Fig. 2), a linear FM pulse is used to generate the surface acoustic waves (SAWs). The SAWs in turn create an optical grating in the optical waveguide which acts as a moving Fresnel zone lens. Thus, the Bragg-diffracted light resulting from a collimated incident light beam will be brought to a focus, and the focal spot sweeps in the focal plane at the acoustic wave velocity. A high-speed photodetector with a sufficiently narrow aperture will register an intense, compressed optical pulse. Since the light energy from the entire aperture of T seconds in length produces a current pulse of length Δt, it is clear that pulse compression has been accomplished with a compression ratio of $T/\Delta t$.

It should be noted that in a fully integrated AO pulse compressor all active and passive components may be formed in a single or small number of substrates (See Fig. 3). As mentioned in the Introduction, such an integrated AO pulse compressor possesses many advantages over its bulk-wave counterpart.
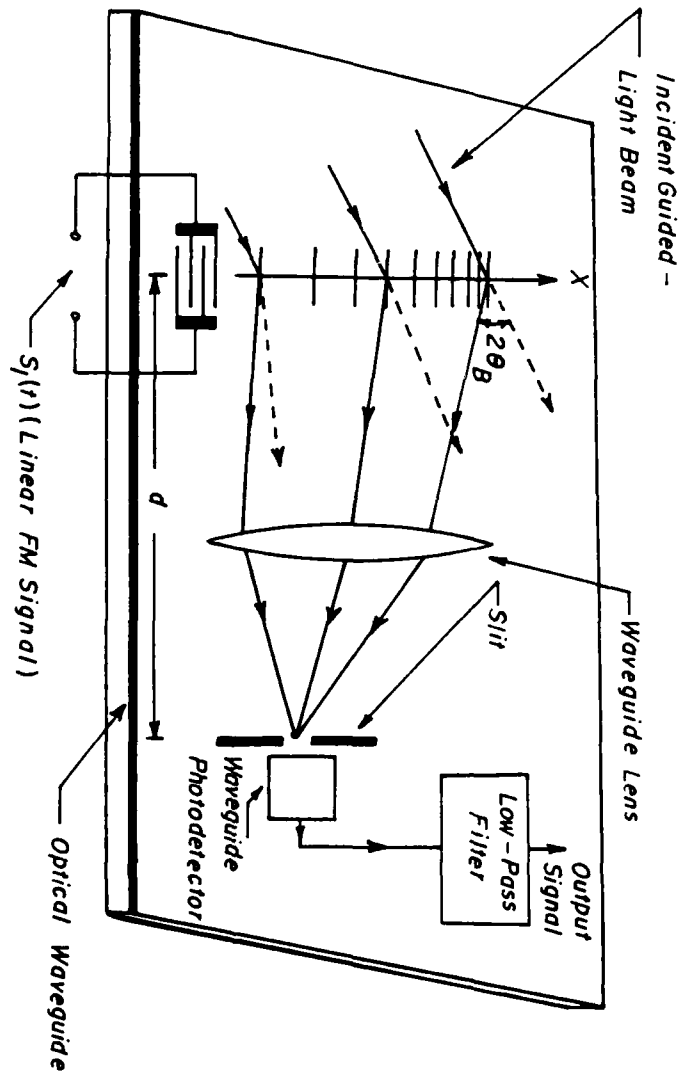
FIG. 3   Guided – Wave Acoustooptic Pulse Compressor Using One
Bragg Cell

B. Major Accomplishments

A continuation of theoretical and experimental studies were carried out. On the theoretical study, a calculation on Bragg diffraction of a plane incident guided-light beam from a surface acoustic wave of a linearly-varying periodicity (See Fig. 2) was completed. As indicated in the above technical discussion, the Bragg-diffracted light is brought to a focus and scans at the acoustic wave velocity. The key parameters of the Bragg-diffracted light are:

$$\text{Focal Length } L_f = \frac{DV}{\lambda \Delta f} = (\frac{V^2}{\lambda}) (\frac{\tau}{\Delta f}) \tag{1}$$

$$\text{Focused Beam Width } d \simeq \frac{V}{\Delta f} \tag{2}$$

$$\text{Scanning Velocity} = V \tag{3}$$

Where
$$\Delta f = \text{Bandwidth Of Linear FM Drive Within The Light Beam Aperture D}$$
$$\tau = D/V = \text{Acoustic Transit Time Across Aperture D}$$

This Bragg-diffracted light may be utilized in two basic applications, namely, optical pulse compression[15] and very high-speed light beam scanning.[7] In the first application which is the concern of this research, it is clear that the width of the compressed optical pulse, Δt, is given by the following relation:

$$\Delta t \simeq \frac{d}{V} \simeq \frac{1}{\Delta f} \tag{4}$$

Finally, the compression ratio, R, which is defined as the ratio of the width of the chirp pulse and the compressed optical pulse width is given as follows:

$$R \equiv \frac{\tau}{\Delta t} \simeq \tau \Delta f \tag{5}$$

Eq. (5) states that the compression ratio or the processing gain of the acousto-optic pulse compressor is equal to the time-bandwidth product of the acoustooptic deflector.

With regard to the second application, it can be shown that the maximum scanning rate (i.e. the number of resolvable spots scanned per second) achievable is $\frac{1}{2} \Delta f$, and the corresponding number of resolvable spots is $\frac{1}{2} \tau \Delta f$. This very

high-speed light beam scanning has also been utilized for high-speed readout of the spectra of integrated optic RF spectrum analyzers.[16]

On the experimental study, we successfully carried out the guided-wave acoustooptic pulse compression experiment described above during the first program year.[17] This was the first successful demonstration of the technique. For this study we fabricated a very wideband deflector in a Y-cut $LiNbO_3$ Ti-diffused waveguide. This deflector employs a three-element tilted-array transducer[6] with the center frequencies of 275, 432 and 648 MHz, and has a measured deflector bandwidth of 500 MHz.[7] In our pulse compression experiment a linear FM pulse of 430 MHz center frequency and broad bandwidth was applied to the second transducer element of the array transducer referred to above (Fig. 4). A collimated and expanded light beam from a He-Ne laser at 6328 $\overset{o}{A}$ wavelength was then Bragg-diffracted from the SAWs. Using a fine slit of variable size we have accurately measured the width of the compressed optical pulse. We have also measured the location of the compressed optical beam (focal length) as a function of the aperture of the light beam and the frequency bandwidth of the linear FM drive signal. A good agreement between the measured values and the predicted ones has been achieved. A 5 nsec width of the compressed optical pulse and a time-bandwidth product of 300 were obtained using a linear FM pulse of 430 MHz center frequency and 160 MHz bandwidth.

In our attempt to achieve a larger time-bandwidth product we have succeeded in increasing the bandwidth and the chirp rate of the linear FM drive. Although further experiments have, to some degree, verified the prediction we have also discovered that as a result of the displacement of the multiple transducers in the horizontal dimension the deflected light spots are also displaced along the horizontal dimension. This horizontal displacement prevented achievement of a much smaller pulse width of the compressed pulse. While we have devised means to compensate for this displacement, we have also been motivated to discover other deflector configurations which do not have the above undesirable features. As a result, two new wideband deflector configurations have evolved from the multiple-tilted transducers of staggered center frequencies. They are tilted-finger chirp transducer and curved transducer of varying finger periodicity.[14] The working principles of these deflector configurations are described in Ref. 14. It suffices to note here that a considerably smaller displacement in the deflected light spots and thus a smaller pulse width is expected to occur in these two deflector configurations.
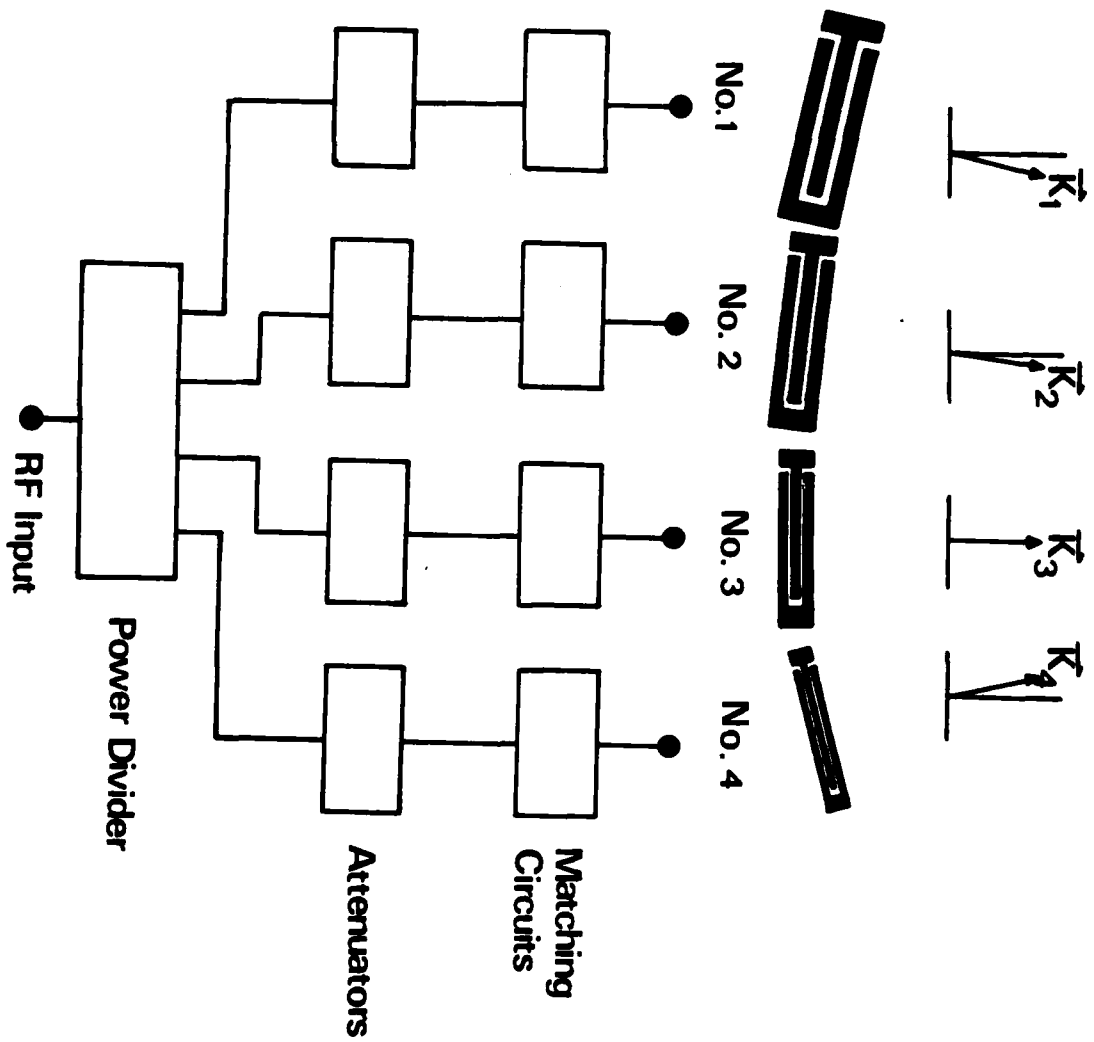
FIG. 4

Multiple Tilted SAW Transducers Of Staggered Center
Frequency And RF Driver Circuits

IV. GUIDED-WAVE ACOUSTOOPTIC CONVOLVERS

A. Technical Discussion

The capability of performing real-time convolution between two rf signals is an important requirement in a radar system because of a great improvement in the signal-to-noise ratio which this technique provides. The time-bandwidth product of the signal processor is an important figure of merit indicative of overall system gain.[18] Real-time convolution using bulk-type acoustooptic interaction configuration was studied by a number of workers in recent year.[9,10,19] Investigation of a guided-wave interaction configuration has been suggested as a result of the progress in the fabrication of both optical waveguides and surface acoustic wave (SAW) devices, and the fact that a more efficient interaction can occur in this configuration.[20] We had earlier demonstrated this more efficient interaction with a guided-wave acoustooptic convolution experiment which employed out- and in-diffused Y-cut LiNbO$_3$ waveguides.[21] This experiment demonstrated that multiple tilted SAW's described earlier can be employed to obtain very good performance figures for convolution with this guided-wave configuration. Multiple tilted SAW's have also been employed in a convolver without optical waveguide to achieve a large time-bandwidth product.[22]

The device configuration which we employed in the experimental study is shown in Fig. 5. An optical waveguiding layer of approximately 2 μm thick was first created on the top of a Y-cut LiNbO$_3$ substrate using in-diffusion technique. Two end-to-end identical SAW array transducers separated at a distance of 1.3 cm, which are characterized by staggered center frequencies (163, 194 and 230 MHz) and propagation axes tilted with respect to each other, were then deposited on the top of the waveguide. Each element transducer has an acoustic aperture of 3.2 mm and the tilt angles between adjacent element transducers are 1.25 and 1.50 mrad.

In the convolution experiment, one pulse-modulated rf signal (say, the reference signal) was applied to one array transducer to generate a SAW and the other pulse-modulated rf signal (the radar signal to be processed) was applied to the other array transducer to generate a second SAW propagating in the opposite direction. The two diffracted light beams overlap and were collected by a lens and then mixed in a P-i-n photodiode detector. The component in the electrical output from the photodetector which corresponds to the convolution of the two rf signals was further processed by means of a heterodyne receiver and then displayed in a wide-band oscilloscope.
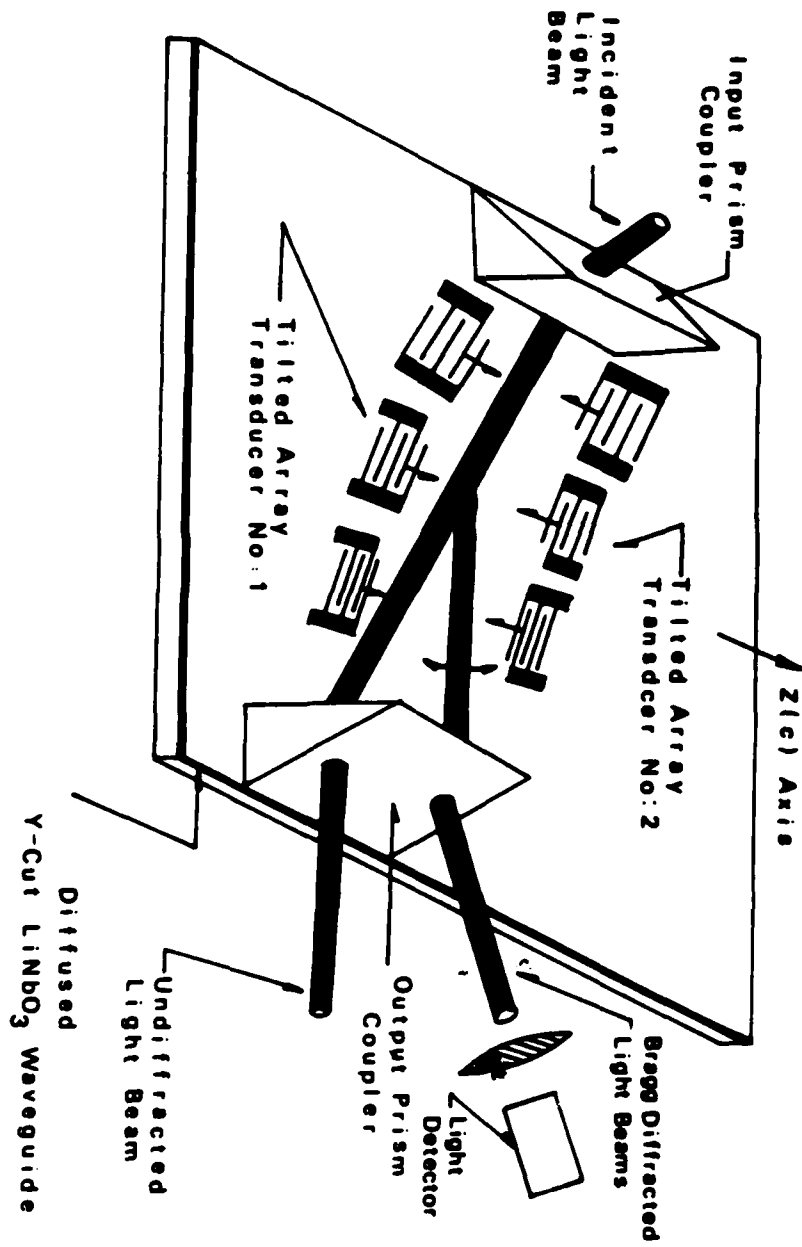
FIG. 5   Convolution Of Wideband RF Signals Using Guided-Wave
Acoustooptic Bragg Diffraction

As indicated in the last Technical Report, the performance figures obtained include: a time-bandwidth product of 305 with a bandwidth of 107 MHz; a dynamic range of approximately 50 db at a total rf power of 310 mW for maximum convolution output; a frequency resolution of 1 MHz (defined at zero convolution output); and an optical through-put coupling efficiency of 18%. A considerably larger time bandwidth product can be achieved by increasing the center frequency of the acoustic wave and/or the aperture of the light beam. For example, using a 1.5 cm light beam aperture and a 680 MHz deflector bandwidth which was obtained recently, a time-bandwidth product of 2950 may be achievable. The 50 db dynamic range of the convolver was obtained at the input light power (before being coupled into the waveguide) of 27 mW. The dynamic range can be greatly increased by using a larger light power and/or a more sensitive photodetector.

In summary, we note that better performance figures are achievable by optimizing the parameters of the convolver described above. We note also that the comparative advantages of such guided-wave acoustooptic convolvers over their bulk counterparts are:

1. More efficient diffraction, less RF drive power;
2. More flexible in the transducer design/fabrication, much easier for the implementation of multiple SAWs;
3. Smaller size, light weight; less critical with isolation and alignment problem;
4. Possibility for batch fabrication, less cost; and
5. Compatible with future integrated/fiber optic systems, suited for a number of wideband applications.

B. Major Accomplishments

A detailed coupled-mode analysis aiming at determining the ultimate performance figures of the acoustooptic convolvers such as bandwidth, time-bandwidth product, and dynamic range is near completion. The findings of this study will be useful for design of a convolver of larger bandwidth and larger time-bandwidth product than the preliminary design described in the above technical discussion.

V. GUIDED-WAVE ACOUSTOOPTIC CORRELATORS

A. Technical Discussion

The ability to perform real-time correlation of two analog signals, i.e. a received signal $S_1(t) + n(t)$, where $n(t)$ is the additive noise, and a reference $S_2(t)$ supplied by the receiver, is one of the key requirements in radar and communication systems. As in pulse compression just discussed, the correlation operation enables achievement of a very narrow output pulse, even when the original signal is very long in time. The pulse width Δt is given by $1/B$, where B is the bandwidth of the signal being correlated. The correlation operation also provides an increase in the SNR over the original received signal, called correlation gain or processing gain. This gain is equal to the time-bandwidth product of the correlator. Thus, two of the most important parameters of a correlator are the bandwidth and the time-bandwidth product just discussed. The other two important parameters are the so-called range window and the time window. Range window is the allowable time error between the received and the reference signals for a correlation peak to be produced, and time window is the total length in time of the correlated signal.

Like the bulk-wave AO correlators the guided-wave AO correlators can be classified into two major types: the spatial-integrating correlators and the time-integrating correlators.[10] The following two subsections give a brief description of the first type and a more detailed description of the second type.

a. Acoustooptic Spatial-Integrating Correlator

Acoustooptic spatial-integrating correlators (AOSIC)[10] perform correlation by integrating the light diffracted by all parts of the signal(s) which are simultaneously present in the Bragg cell. A possible guided-wave version is shown in Fig. 6. The received signal plus noise, $S_1(t) + n(t)$, to be correlated is fed into the first SAW transducer, producing a spatial display of a given time window of the received signal. This spatial display is multiplied by that produced by a time-reversed reference signal, $S_2(-t)$, applied to the second SAW transducer. The diffracted light is then spatially integrated onto the waveguide photodetector and resulting in the correlation signal. The advantage of using a second transducer for the reference signal is that a large variety of signal waveforms can be correlated by properly varying the reference signal. Note that this type of correlator has a large range window but a
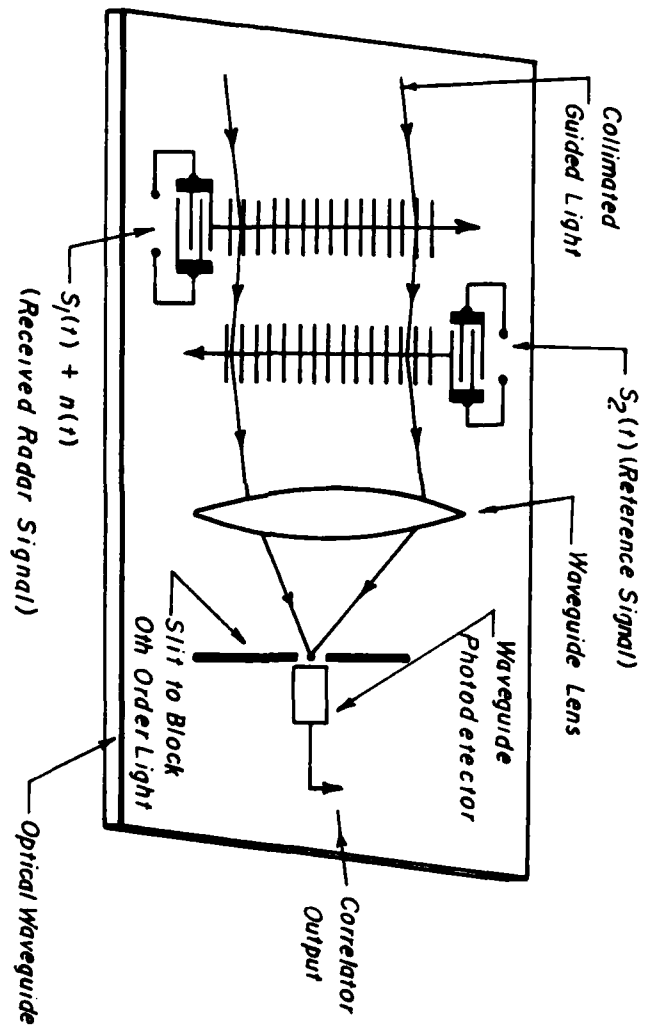
FIG. 6   Guided – Wave Acoustooptic Spatial – Integrating Correlator

limited time window and thus a limited time-bandwidth product. Using a uniform guided-light beam aperture of 1.5 cm the maximum time window achievable is 4.35 µsec. Thus, a time-bandwidth product of 2950 can be expected if a modulator of 1 GHz bandwidth is employed.

b. Acoustooptic Time-Integrating Correlator

Acoustooptic time-integrating correlators (AOTIC)[23,24] perform correlation by using a closely spaced photodetector array to integrate in time for each point within the Bragg cell. A fully-integrated or monolithic guided-wave version is depicted in Fig. 7. The signal to be correlated, $S_1(t)$, is added with a bias voltage V_1 and used to modulate the intensity of a coherent light source. The modulated light is then collimated and diffracted by the acoustic wave produced by an RF carrier which is amplitude-modulated by the reference signal $S_2(t)$. A proper choice of bias voltage V_2 would ensure that the intensity of the diffracted light is linearly proportional to $S_2(t)$. The diffracted light is then collected by a lens, filtered, and imaged onto a photodetector array. It can be shown that, if $S_1(t)$ and $S_2(t)$ have zero mean values, the intensity of the diffracted light at the output of the photodetector array contains the correlation signal between $S_1(t)$ and $S_2(t)$. This correlation signal is displayed in space but can be read out in time using a CCD array. Since the correlation is performed in time rather than in space this type of correlator is potentially capable of a very long processing time which is determined by the time constant of the photodetector array. Furthermore, since both the coherent light source and the AO Bragg cell can be modulated at GHz bandwidth, this type of correlator is also potentially capable of very large bandwidth, and thus very large time-bandwidth product.

B. Major Accomplishments

Our preliminary experiments using surface acoustic waves (centered at 125 MHz) in a Y-cut $LiNbO_3$ waveguide and a He-Ne laser light (6328 Å), modulated by a bulk-wave AO modulator and coupled into and out of the waveguide through a pair of rutile prisms, have demonstrated a processing time of 7 milliseconds and a time-bandwidth product of 1.5×10^5.[25] Figs. 8 and 9 show, respectively, the auto-correlation outputs of rectangular pulse train and pseudo-random code.
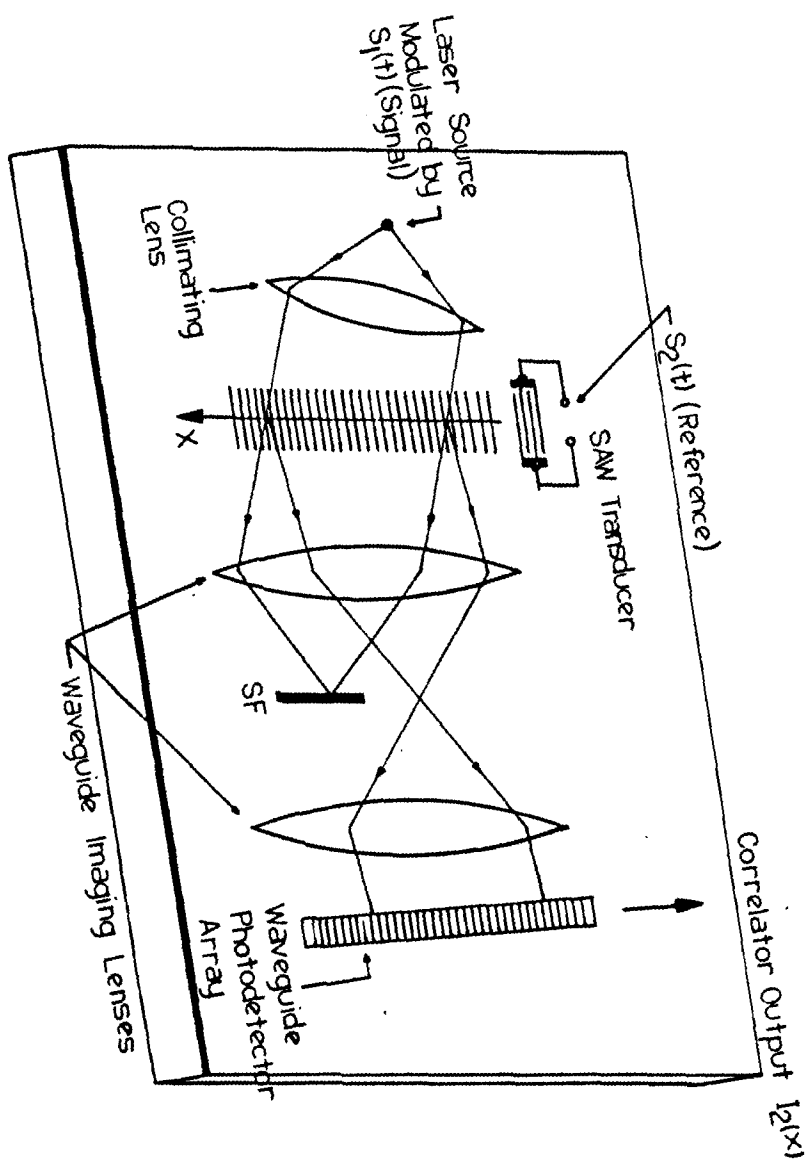
FIG. 7   Guide-Wave Time-Integrating Acoustooptic Correlator

(a)

(b)
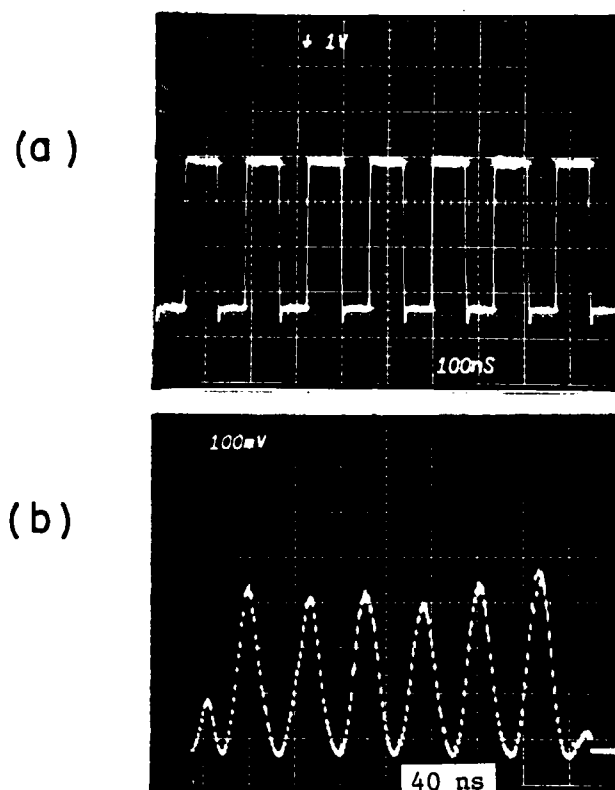
FIG. 8

INPUT AND OUTPUT WAVEFORMS OF THE GUIDED-
WAVE TIME-INTEGRATING ACOUSTOOPTIC CORR-
ELATOR.

(a) Rectangular Input Pulse Train to Both Modu-
lator and Deflector.

(b) Triangular Autocorrelation Output.

(Horizontal Scale: 100 ns Per Major Division.)
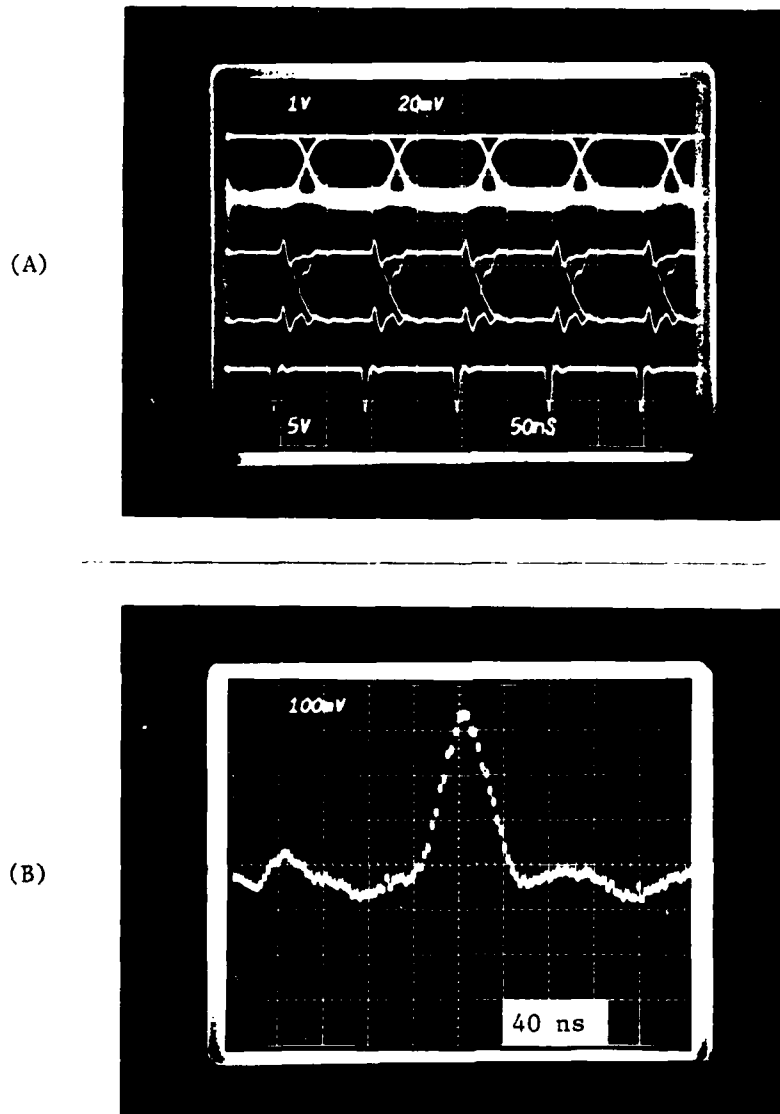
FIG. 9   AUTO-CORRELATION OUTPUT OF PSEUDO-RANDOM CODE WITH
A CHIP RATE OF 1/100 nsec

(A)   Top Trace: Output Light From AO Modulator
      Middle Trace: Input Code To Be Correlated
      Bottom Trace: Clock Pulses Of Pseudo-Random
                      Code Generator

(B)   Correlation Output At Expanded Time Scale

The AlGaAs multilayer structure is a potential substrate for the monolithic AOTIC module shown in Fig. 7. In this case the light source takes the convenient form of a distributed feedback[26] or Bragg reflector laser.[27] However, most of the other passive and active components for this monolithic module remain to be developed. At present, silicon and lithium niobate are the two most promising substrates for implementation of a hybrid AOTIC module. In the former the light source such as a GaAlAs DH laser diode is butt-coupled[28] to one edge of the Si substrate. In the latter both the GaAlAs DH laser diode and the photodetector array are butt-coupled to the edges of the $LiNbO_3$ substrate[29] (See Fig. 10). A model design has shown that a Y-cut $LiNbO_3$ plate having a substrate area of 2.5x6 cm is sufficient to accommodate all passive and active components. In view of the fact that high-quality optical waveguides,[30,31] geodesic lenses,[32] and wideband high-efficiency Bragg deflectors/modulators have been successfully fabricated in the $LiNbO_3$ substrate, the hybrid structure as illustrated in Fig. 10 appears to be the most attractive approach for the present. Based on the aforementioned preliminary results,[25] the hybrid AOTIC should be capable of providing much better performance figures.[33] Implementation of this hybrid AOTIC is being carried out and the experimental results will be reported in the future.

VI. INTEGRATED ACOUSTOOPTICAL CIRCUITS FOR WIDEBAND REAL-TIME RADAR SIGNAL PROCESSING

A. Introduction

In view of the recent progress on fabrication of GHz bandwidth thin-film AO Bragg modulators (deflectors) and miniature laser sources, wave-guide lenses, and photodetector arrays, integration of all these passive and active components on a single substrate or a small number of substrates is becoming a reality. The resulting integrated AO modules or circuits should possess a number of attractive features such as low electrical drive power, small size, light weight, less susceptibility to environmental effects, and potentially lower cost.[11]

Using an RF spectrum analyzer as an example, a fully-integrated or monolithic AO circuit is depicted in Fig. 11. The AlGaAs multilayer structure is a potential substrate for this monolithic module. In this case the light source takes the convenient form of a distributed feedback or Bragg reflector laser.

FIG. 10

Laser Diode

SF #1

Waveguide Lens

WL #1

Acoustic Absorber

SAW Transducer

WL #2

Diffracted Light

Z

Y

X

SF #2
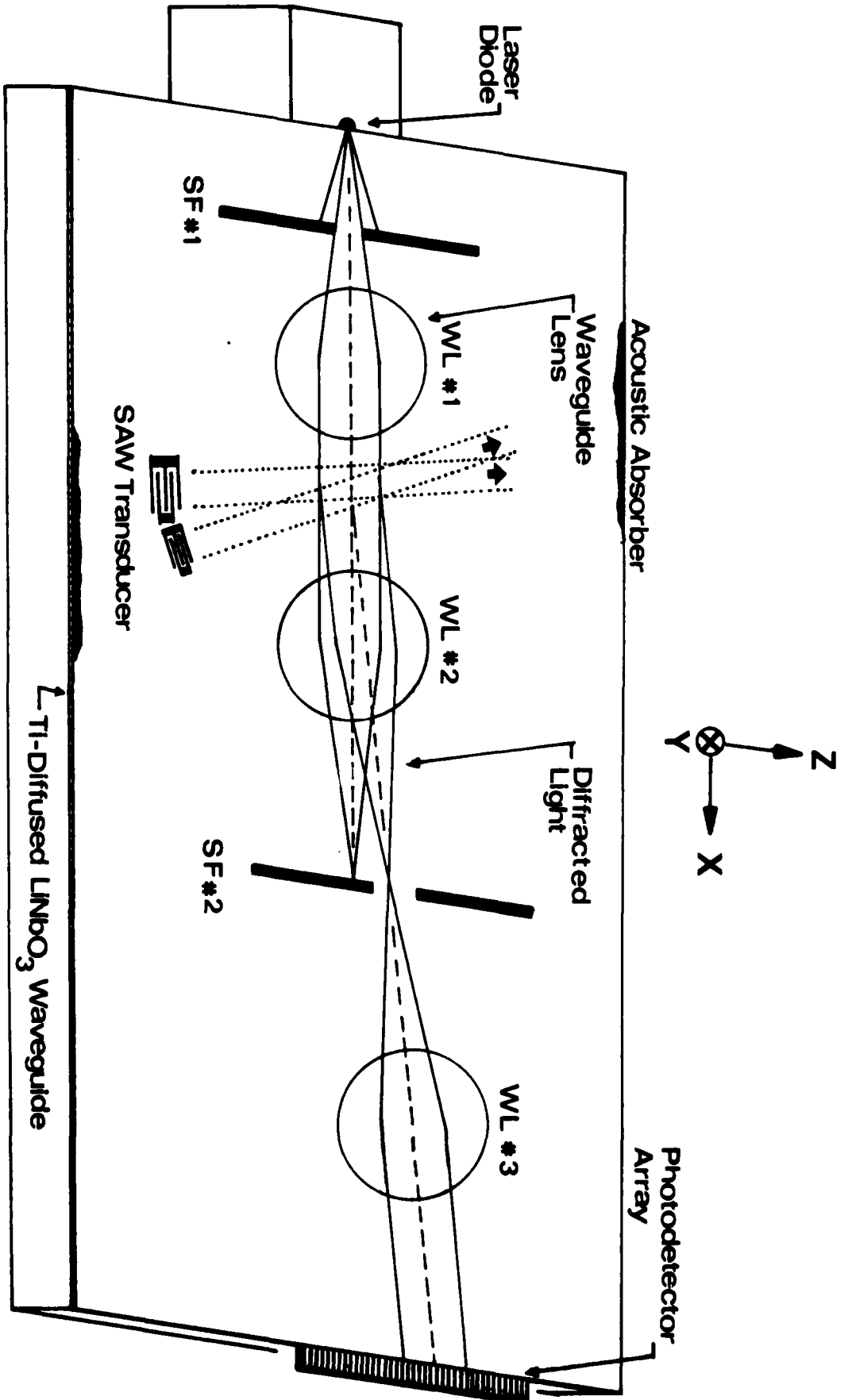
Ti-Diffused LiNbO₃ Waveguide

WL #3

Photodetector Array

An Acoustooptic Time-Integrating Correlator Using Hybrid Optical Waveguide Structure
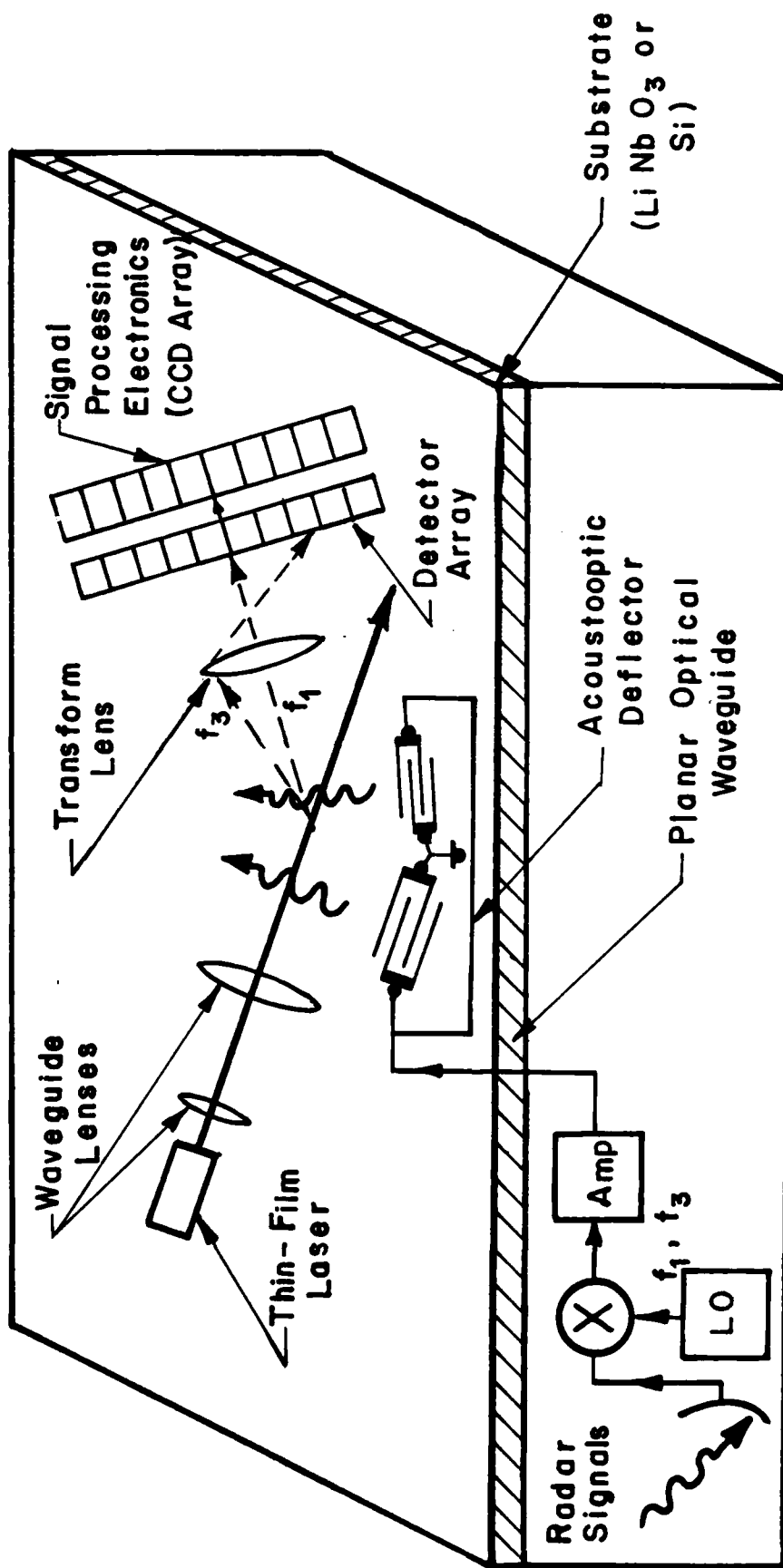
FIG. 11   Integrated Optic RF Spectrum Analyzer
(An Example of Integrated Optics Circuitry)

However, most of the other passive and active components for the monolithic module remain to be developed. Although the AlGaAs multilayer structure is the ideal substrate for the monolithic modules the hybrid structure using a LiNbO$_3$ substrate, as illustrated in Fig. 12, constitutes the most realizable approach for the present. In this hybrid structure both the GaAlAs DH laser diode and the photodetector array are butt-coupled to the edges of the LiNbO$_3$ substrate. A model design has shown that a Y-cut LiNbO$_3$ plate having a substrate area of 2.5x8 cm is sufficient to accommodate all passive and active components. In view of the fact that high-quality optical waveguides, geodesic lenses, and wideband high-efficiency Bragg deflectors/modulators have been successfully fabricated in the LiNbO$_3$ substrate, the hybrid structure as shown in Fig. 12 appears to be the most attractive approach for the present. Implementation of this hybrid integrated optic spectrum analyzer is being carried out at a number of research laboratories in the United States. The integrated optic RF spectrum analyzers, when fully developed, are expected to possess two major advantages: 1. increased performance and reduced cost over both currently employed technology and competing technologies, and 2. reduced size and increased compactness.

B.   Integrated Acoustooptic Time-Integrating Correlators

We had earlier identified acoustooptic time-integrating correlation of wideband rf signals as the next most important and immediate applications of such integrated AO circuits.[12-14,25,33] As in the spectrum analyzers, although the AlGaAs multilayer structure is the ideal substrate for the monolithic AOTIC modules the hybrid structure using a LiNbO$_3$ substrate, as illustrated in Fig. 10 constitutes the most attractive and realizable approach for the present. A model design has shown that a Y-cut LiNbO$_3$ plate having a substrate area of 2.5x6 cm is sufficient to accommodate all passive and active components. Based on the aforementioned preliminary results,[25] this hybrid AOTIC should be capable of providing much better performance figures.[33] Consequently, implementation of this hybrid AOTIC constituted the major task of the BMDATC program during the past half year. Some encouraging results have been obtained. We have successfully butt-coupled a He-Ne laser light at 6328 Å to the LiNbO$_3$ waveguide and butt-coupled the Bragg diffracted light out of the LiNbO$_3$ waveguide. We are in the process of mastering the technique for fabricating geodesic lenses. We expect no major difficulty in realizing a preliminary module once the geodesic lenses are fabricated.
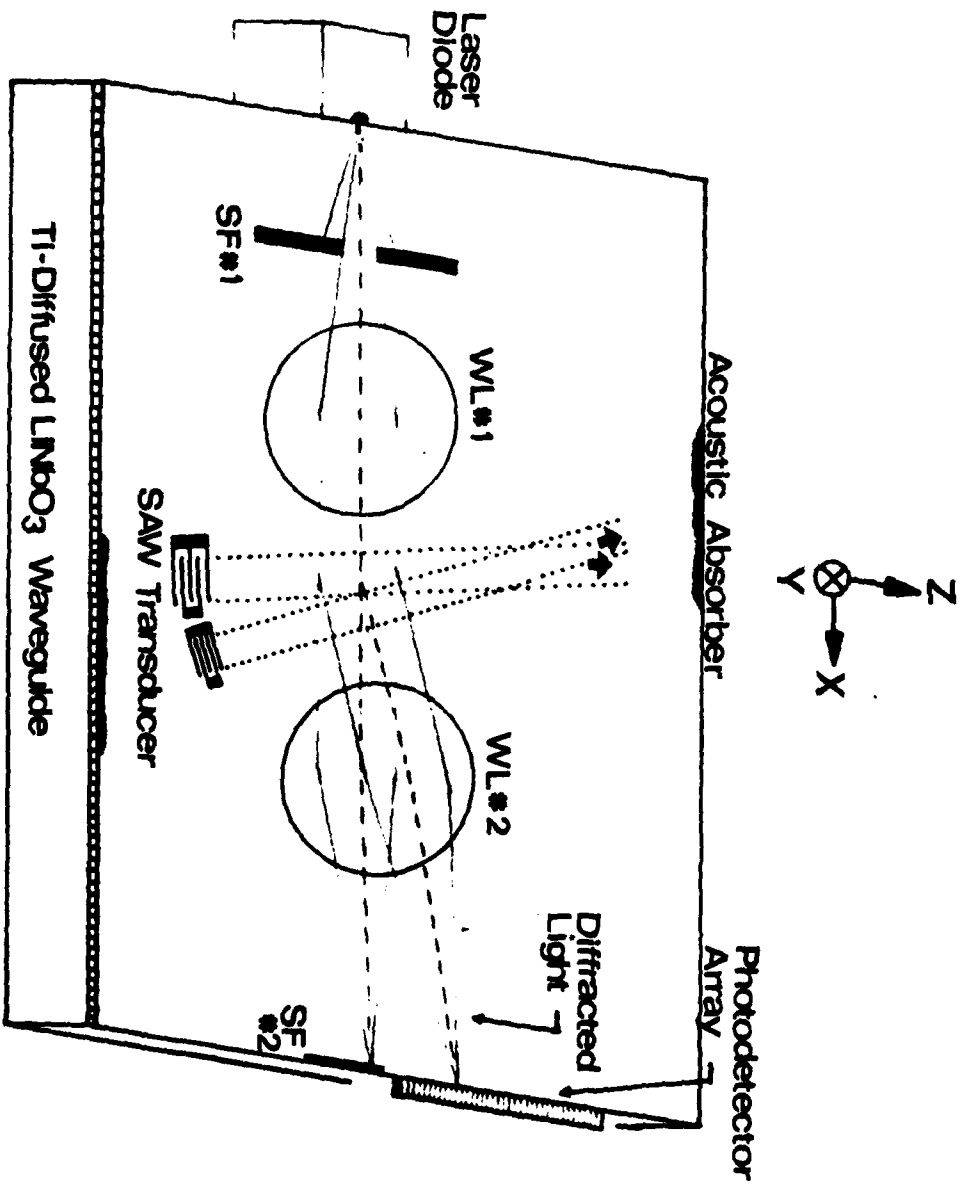
FIG. 12

An Acoustooptic Spectrum Analyzer Using Hybrid Optical
Waveguide Structure

C.   Future Plan

In view of the great current interest in Bulk-wave acoustooptic time-inte-
grating correlators[11,24] and the many inherent advantages with the Integrated-
Optic version, and the fact that considerable progress has been made under the
BMDATC support, we plan to continue this research if BMDATC can provide the
necessary support in the near future. The specific tasks of this projected re-
search are: 1. to complete the implementation of the hybrid integrated optic
time-integrating correlator as shown in Fig. 10; 2. to study its performance
characteristics/figures; 3. to establish design parameters and guidelines,
and ultimate capabilities; 4. to identify and study suitable signal processing
architectures.

VII. CONCLUSIONS

Recent research in planar guided-wave acoustooptics has made possible
realization of high-performance thin-film Bragg modulators and deflectors with
GHz bandwidth in Y-cut $LiNbO_3$ waveguides. Together with the progress on fab-
rication of miniature laser sources, wave-guide lenses, and photodetector
arrays, integration of all or most of these components on a common substrate is
becoming a reality. The resulting integrated AO modulators or subsystems
possess a number of attractive features such as low electrical drive power,
small size, light weight, less susceptibility to environmental effects, and
potentially lower cost. Clearly, these integrated AO modules or subsystems
will find a number of unique applications in wideband multichannel radar sig-
nal processing and communications. One application that has already received a
great deal of attention and interest is the real-time spectral analysis of
wideband RF signals. Other applications such as time-integrating correlation,
convolution, pulse compression and matched filtering of rf signals, and multi-
port deflection and switching of optical signals in a single-mode multichannel
communication system should be far behind. The preliminary performance figures
that have been measured in some of these applications have demonstrated some
of the attractive features.

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